Magnetic Radular Teeth and Geomagnetic Responses in Chitons

BY

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(1 Text figure)

SPENCER THORPE discovered that chiton radulae have ferromagnetic teeth (reported by TOMLINSON, 1959). Analysis by LOWENSTAM (1962, 1967; TOWE & LOWENSTAM, 1967) revealed that the material on the teeth contains magnetite, lepidocrocite and iron-bearing apatite. Although CAREFOOT (1965) suggests that this material is primarily an adaptation to feeding, LOWENSTAM (1962) speculated that this magnetite material might enable homing orientation in chitons, but EIBSCHUTZ *et al.* (1967) dispute this.

FRANK A. BROWN, JR., and his colleagues have done much work with magnetic compass reactions, primarily with the snail *Nassarius (Illyanassa) obsoletus* (SAY, 1822) and with planarians (1965). Work prior to 1964 is reviewed by MADELEINE BARNOTHY (1964). More recent work on magnetic field orientation includes bacteria (BLAKEMORE, 1975; FRANKEL *et al.*, 1979), bees (GOULD *et al.*, 1978), flies (BECKER, 1965; BECKER & SPECK, 1964; PICTON, 1966; WEHNER & LABHART, 1970), elasmobranchs (H. R. BROWN *et al.*, 1979) and birds (BOOKMAN, 1977; KEETON, 1971; KREITHEN & KEETON, 1974; SOUTHERN, 1975; WALCOTT *et al.*, 1979, W. & R. WILTSCHKO, 1972). KIRSCHVINK & LOWENSTAM (1979) studied chiton magnetite with implications for marine sediment natural magnetizations.

RATNER & JENNINGS (1968) tested chitons in magnetic fields ranging from normal to 8 000 gauss. The chitons showed reduced movement in above-normal magnetic fields. They reported that the chiton seemed equally likely to orient in any compass direction.

The reduction of chiton movement by stationary magnets may be due to the pull on the ferromagnetic radula. If this is so, then a moving magnetic field might be very stimulating indeed. The handiest moving magnetic field readily available in most laboratories is a standard laboratory magnetic stirrer. One of us (J.T.) put a *Lepidozona* sp. on a Corning HCT Plate Stirrer, of approximately 700 gauss, and in 10 minutes the chiton had made a backing turn of almost 360°. Several species of chitons have clearly indicated detection of the field. Species include *Katharina tunicata* (Wood, 1815), *Lepidozona cooperi* (Carpenter *in* Pilsbry, 1892), *L. mertensii* (Middendorff, 1846), *Mopalia lignosa* (Gould, 1846) and *Nuttallina californica* (Reeve, 1847).

In order to determine that it was the rotating magnetic field and not vibration or other extraneous stimulation, we placed a sheet of steel (16 gauge) between various brands of stirrer and the chiton. The response was greatly reduced, to the extent that movements could not be distinguished from non-rotating (power-off) conditions. If the chiton moved with its anterior end off the sheet of steel, or if the chiton were placed on a thin sheet of plastic over the steel and the steel pulled out gradually, a very strong response was shown immediately after the radular area was exposed to the rotating magnet.

Since it can be demonstrated that chitons can detect this magnetic field, it would not be surprising if they can detect the earth's magnetic field. Field measurements were made by all three authors independently, and by several other students as well, although the initial observation was Ballering's. A compass was placed directly above each chiton seen, the bezel was turned until the needle indicated north, and the headings were recorded and plotted on polar coordinates (Figure 1: A-C, I-K). It can be seen from inspection that the predominant orientation is northerly. Chi-square tests of chitons observed oriented 271-89° (northerly) versus 91-269° (southerly), with equal numbers expected, yielded probabilities of less than 1 in 10 000 ($P < 0.0001$) that the northerly orientation was due to chance. This general conclusion was reported to the Western Society of Naturalists at their annual meeting in 1973. In all cases, care should be exercised to determine posi-

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tively which end of the chiton is anterior, by removing the chiton gently and noting the mouth. In badly eroded or overgrown specimens this is sometimes difficult to determine by simple dorsal inspection. It should be further noted that the species vary in showing an orientation, with *Nuttallina californica* the weakest, the species of *Mopalia* good, and *Katharina tunicata* the strongest. In addition, certain times of the year do not yield good orientations. We have found that the summer is best and the winter is worst for orientation.

Several students in the invertebrate behavior laboratories at San Francisco State University became involved in this project, and references hereafter are to their unpublished term papers, copies of which are available from Tomlinson.

In order to determine the degree of influence of the earth's magnetic field on the orientation of chitons, it was suggested that the earth's field may be blocked by placing the chitons in an iron container, with an aluminum container, which does not block the magnetic field, as a control. Ballering tried this and the results were not quite significant. Stephen Vital placed over a hundred chitons (*Mopalia muscosa*) on identically-painted sheets of aluminum or steel plate. The chitons initially deposited facing east or west on the aluminum plates for 30 minutes oriented northerly very significantly ($P < 0.01$, Figure 1D), while those placed on the steel plates did not (Figure 1E). Chitons placed on rock with steel pipes placed over them did not orient significantly (Figure 1F). David Klise used steel versus aluminum roaster pans into which he placed specimens of *M. muscosa*. Two two-hour runs were made, with the containers rotated 180° between runs to eliminate

(adjacent column →)

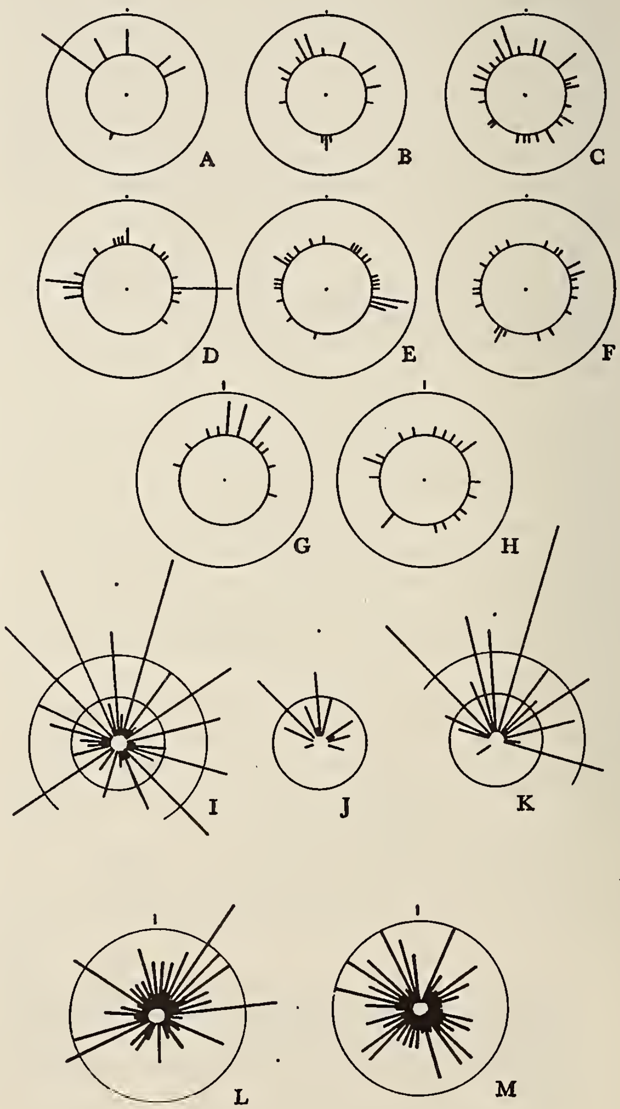

Figure 1

Polar coordinate plots of the compass headings (anterior ends) of chitons at various intertidal areas of central California. Length of line is proportional to number of individuals: Circle is 5, broken circle 10 individuals. A dot above each array indicates true north, a line indicates magnetic north. All are *Mopalia muscosa*, except B and C.

A - C. Data by El-Ahmadiyyah:
- A. Pebble Beach State Park. 37°14′N[2]
- B. *Katharina tunicata*. Fort Ross. 38°31′N[1]
- C. *Katharina tunicata*. Bodega Bay. 38°18′N[1]

D - F. Data by Vital, all from Pillar Point, 37°30′N
- D. On 1 mm plate aluminum[1]
- E. On 6 mm plate steel
- F. Surrounded by steel pipe 4 - 6 mm thick

G - H. Data by Klise, all from Mussel Rock. About 37°40′N
- G. In aluminum roaster pan with lid[2]
- H. In steel roaster pan with lid

I - K. Data by Ballering
- I. RCA Reef. 37°56′N[1] (see text)
- J. Duxbury Reef. 37°54′N[2]
- K. Pebble Beach State Park. 37°14′N[2]

L - M. Data from Reilly, all from Duxbury Reef. 37°54′N
- L. In aluminum pans with lids[1]
- M. In iron and steel pans with lids

[1] Significant at the 0.01 level
[2] Significant at the 0.001 level

any position effect. Data from the combined trials are given in Figures 1G and 1H. The results were significant at the 0.1% level ($P < 0.001$). Reilly repeated the last experiment at Duxbury reef (37°54′N) in May and June, 1978. Three aluminum pans (175 x 175 x 50 mm) held 25 randomly-placed *M. muscosa,* while two iron pans (one cast-iron 75 mm deep and 240 mm in diameter; one a Teflon-coated steel pan 50 mm deep and 250 mm in diameter, both with lids) also held 25 *M. muscosa.* After 2 hours in the pans, the lids were removed and the heading of each chiton was determined by placing a compass above the chiton and turning the bezel until it indicated north. The chiton was then removed from the pan conclusively to determine the anterior end. The chitons were switched to the pan of the alternative metal, and run for another 2 hours. This procedure was followed on 2 separate days, with a third day added without a second run in the alternative pan. A total of 98 chitons were tested, the data for each metal pooled, and shown in Figures 1L and 1M, and are significant at the 1% level ($P < 0.01$). It is clear that they orient in the aluminum pans, and not in the iron pans, as expected.

Individual dark-colored (iron-bearing) radular denticles have aligned magnetic moments. When placed on glass and approached with a bar magnet, the teeth will spin and the pointed cusps will align toward the north magnetic pole in most denticles. An alignment was reported in a personal communication by William A. Newman of Scripps Institution of Oceanography; he had reportedly detected this shortly after the original magnetic report in 1959. Wayne Hughes of our laboratories found it independently. Reilly and Tomlinson added iron powder to water containing a radula (*Mopalia muscosa*) to determine the microscopic alignment of the field. The iron adheres to the dark areas, especially at the points.

It has been found (by Jameel El-Ahmadiyyah) that the aligned magnetic moment is capable of turning the entire chiton to face northerly on low-friction floats. To demonstrate this, place 3 chitons aligned parallel on a float (*e. g.,* a piece of wood) in a quiet pool of water with no iron nearby. The chitons (depending on the species and the time of year) will usually cause the float to turn until the anterior ends of the chitons face north, without necessarily moving on the float. We have found that isolated radulae will do this when floated on slivers of wood.

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SUMMARY

Chitons respond vigorously to a rotating magnetic field. In central California some chitons tend to face northerly in the sea. This is also seen when the chitons are placed in aluminum containers; in steel containers, which block most of the earth's magnetic field, they show no significant orientation. Individual dark-colored denticles on the radula have aligned magnetic moments. When chitons or their excised radulae are floated on relatively friction-free blocks of wood on water and protected from drafts of air, they will align to magnetic north as a compass. All of these orientation phenomena are seen more strongly in the summer, becoming lost in the winter.

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